Evaluation of the effect of flexible demand on the design and operation of Hybrid Energy Systems

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Abstract

Many remote locations such as islands are not connected to the main electricity grid and instead rely on a microgrid powered by diesel generators. Most of these locations have excellent renewable resources and in recent years Hybrid Energy Systems (HES) which combine renewable generation with backup diesel generators and battery storage have become cost competitive for these locations. In most cases the diesel generators provide about 10% of the energy demand because most renewable generation is non-dispatchable and energy storage is more expensive. In addition, a significant fraction of the renewable electricity generation needs to be curtailed because the supply is larger than the demand and the storage is full. The wasted renewable electricity increases the capital and running costs while the backup diesel generator has high greenhouse gas emissions. The addition of Demand Side Management (DSM) to HES offers the potential to reduce both the diesel fraction and the wasted renewable generation. In DSM electricity demand is shifted from times with lower renewable supply than demand to times with surplus renewable supply. In contrast to energy storage, these measures can have lower capital costs and have no inherent losses (batteries have charge/discharge and self-discharge losses). In this contribution, DSM is added to the in-house simulation framework for the design and optimisation of HES. The framework is used to evaluate HES with and without DSM for an off-grid island in the Mediterranean and in the North of Scotland. The comparison of different levels of DSM with respect to greenhouse gas emissions and electricity costs shows that DSM can reduce both objectives.

1 Introduction

In many remote locations the electricity is generated locally and supplied through a microgrid which is not connected to the main electricity transmission network or has only a very weak connection. The required electricity is usually generated with diesel generators and thus the system is reliant on imported and often expensive fossil fuels with the resulting problems: high electricity costs and local pollution. However, in recent years an increasing number of so called Hybrid Energy Systems (HES) which combine renewable electricity generation with energy storage and backup generation, have been installed [1], [2]. While it would be desirable to use only renewable energy sources, the variable and more importantly non-dispatchable nature of most renewable electricity generation (with the exception of biomass and some forms of hydro-electricity) would require massively oversized generation capacity to fulfil the demand at all times. The integration of energy storage (usually batteries) enables the shifting of renewable energy from times when the renewable supply is larger than the demand to times with higher demand than supply. This increases the utilisation of the renewable generators as well as the renewable energy fraction of the system, i.e. fraction of the total energy demand covered from renewable generators. However, a very large battery system is required to achieve a fully renewable system and large parts of this battery would only be used infrequently. Thus HES usually contain a fossil fuel based backup generator. One of the challenges of HES in remote and sparsely populated areas is the high demand coincidence factor (ratio of the maximum demand of a group of customers to the sum of the individual maximum demands) [3]: for less than 100 customers the coincidence factor is over 0.2 while it is around 0.1 in conventional distribution networks. This means the generation equipment needs to be able to cope with larger demand spikes and thus needs to be oversized. The use of Demand Side Management (DSM) measures can be beneficial in reducing these demand spikes and in balancing the supply and demand in microgrids.

The development of HES for off-grid applications started in the late 1970s and has seen significant growth in recent years due to the cost reduction in renewable generation and energy storage. However, significant challenges remain in the design and control of HES with economic and ecological benefits [4]. While the wind/PV/diesel/battery HES is the most common system in the academic literature and in practice, a number of studies have considered alternative renewable resources, e.g. biogas and small-scale hydro [5] or wave energy converters [6] [7], and different energy storage options, e.g. pumped hydro storage [8] and hydrogen [9].

A careful consideration of the renewable resource, demand and available equipment is crucial to design and size a HES which can provide reliable energy at the lowest possible cost. It was realised from the beginning that simulation tools are required to evaluate and optimise these potentially conflicting objectives which depend on a large number of design parameters [10], [11]: system parameters and costs for each generator; conversion and energy storage type; demand profiles; renewable resource profiles. For example, Castle et al. [11] developed a computational tool for the automatic sizing of wind/photovoltaic (PV)/diesel/battery HES with respect to Levelised Cost Of Electricity (LCOE). They concluded that HES which allow a small percentage (e.g. 5%) of the load to be supplied by a diesel generator require a much smaller battery capacity (about 5 times smaller) compared to fully renewable systems. The optimal sizing [12]–[14] and control [15] of HES has been a continuous focus of many studies in recent years and an overview of the develop software tools is given by Sinha and Chandel [16]. The de-facto standard for HES simulation is HOMER which was developed by the U.S. National Renewable Energy Laboratory [17]. However, HOMER has limitations in the integration of novel renewable generators such as wave energy converters and in the optimisation of the HES with respect to multiple objectives.

In recent years DSM has received increased attention for the wider energy system [3] and also for HES [18], [19]. DSM can be used to shave the demand peaks, to fill the demand troughs and, particularly in HES, to follow the renewable supply. The reduction of peaks is particularly relevant for HES which have a larger coincidence factor [3]. DSM plays a similar role to energy storage in balancing the demand and supply but compared to energy storage can be a low cost solution with no inherent energy losses. Gudi et al. [20] presented a simulation platform that uses optimisation methods to distribute the energy generated by a given HES to various loads. In their case the optimal distribution of the loads leads to a cost reduction of around 16%. The simulation tool HOMER contains options to simulate measures to increase efficiency and deferrable loads which can be used to simulate DSM. Bognar et al. [21] use the deferrable load model in HOMER to evaluate the effect of adding flexible seawater desalination to a HES for the Caribbean island Petite Martinique. Most of the water demand of the island is produced with surplus energy from the HES. Sea water desalination offers the potential for DSM with a large shift window due to the ease of fresh water storage. Krumdieck and Frye [18] use HOMER to design a HES for the New Zealand research station at Scott Base in Antarctica. They use a custom DSM modelling tool to evaluate the DSM potential of shifting the laundry load to times with surplus renewable supply.

In this contribution the effect of DSM on the operation, efficiency and cost of HES is evaluated. A DSM model is added to the in-house HES simulator which allows the optimisation of HES combining wind turbines, solar PV panels, wave energy converters, energy storage and diesel units. The effect of various levels of DSM on the design and operation of two HES, the Greek island Astypalaia and the island Westray in the North of Scotland, are shown.

2 HES simulation and optimisation framework

The optimisation framework for HES was introduced by Friedrich and Lavidas at OSES2015 [6]. Briefly, the simulation and optimisation framework models a number of electricity and heat generation units (solar PV, wind turbines, wave energy converters, diesel generators, boilers, heat pumps, resistive heating, solar thermal) as well as electricity and thermal energy storage (batteries and hot water tanks) units. The individual components are described by parameterised models which give the energy flows between the HES components and offer a good balance between complexity and accuracy [4]. A HES is formed by connecting the components through a DC bus which supplies the AC load through a DC/AC converter; see Figure 1.

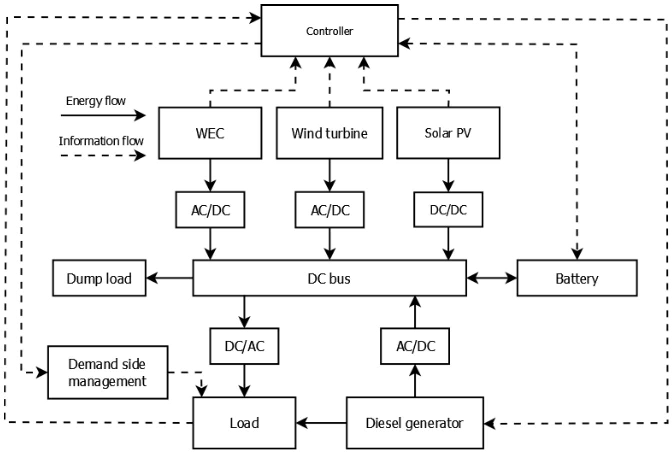

Figure 1: Schematic of the proposed HES with demand side management.

A simple control scheme ensures that the load is met at all times through a combination of the renewable generators, energy storage and backup generators. The framework is linked to multi-objective optimisation methods which enable the optimisation with respect to multiple and often conflicting objectives.

2.1 Demand side management

In this contribution a DSM model similar to the one developed by Krumdieck and Frye [18] is added to the in-house HES simulation and optimisation framework. In this model the flexible demand is defined by the amount of shiftable demand and by the size of the shift window. Here the shiftable demand is given as a percentage of the total demand and the shift window is the maximum time the shiftable demand can be held back. In every time step of the simulation this flexible demand is checked before utilising the backup diesel generators or before curtailing the renewable generation. The fulfilment of the flexible demand depends on the balance between the renewable supply and fixed demand. If there is a supply shortage only the flexible demand at the end of the shift window is fulfilled, i.e. for a shift window of 5 hours only the shiftable demand which has already been delayed for 5 hours is fulfilled. On the other hand, if there is surplus renewable supply as much as possible of the flexible demand is fulfilled.

In this contribution we are only looking at a single flexible demand defined through the shift percentage and shift window length, i.e. 5% DSM for 5 hours means that 5% of the total demand is shiftable demand with a shift window length of 5 hours. However, the simulation framework is flexible enough to handle multiple flexible demands with different shift windows. Furthermore, no losses or costs are associated with the DSM measures. This simplification enables the evaluation of the maximum potential of DSM.

3 Case studies

In this contribution two case studies with different demand and resource profiles will be investigated. The Greek island Astypalaia has a good solar resource and a summer demand peak due to the tourist season and the use of air conditioning units. The North of Scotland has a winter demand peak which aligns to some extend with the wind resource.

3.1 Astypalaia

Most of the Greek islands have isolated electricity grids which are dependent on oil fired electricity generation. The resulting high electricity costs have led to proposals to develop HES on Greek islands to achieve greater energy autonomy [22]. The deployment of HES in Greek islands was investigated in recent years and a number of real systems have been deployed, e.g. Lemnos Island [2].

The first case study for Astypalaia was originally presented at OSES2015 [6]. Briefly, Astypalaia is an island in the Dodecanese Archipelago in the south of the Aegean Sea with about 1300 inhabitants. The island has an isolated electricity grid and the electricity is provided by a small fossil fuel power plant. In 2003 the island had a peak demand of 1.78 MW and an annual electricity consumption of 5419 MWh [8]. The electricity demand as well as the wind and wave resource are described in [6]. The electricity demand and solar resource are given in Figure 2 and Figure 3. The schematic in Figure 1 shows the HES for Astypalaia.

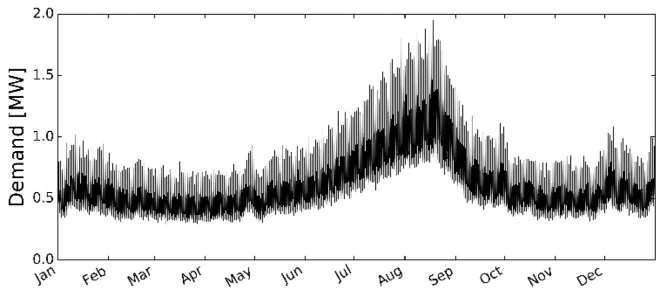

Figure 2: Synthetic electricity demand curve for Astypalaia.

While the solar irradiance is high throughout the year, the summer demand peak is only partly aligned with the solar resource. The average demand in August is more than double the average demand in spring and autumn. This high summer demand is due to an increase in tourism and the increased use of air conditioners. These air conditioners offer the potential to shift some of the electricity demand by cooling the property when there is surplus of renewable electricity. This assumes that a moderate variation in indoor temperature is acceptable to maintain human comfort.

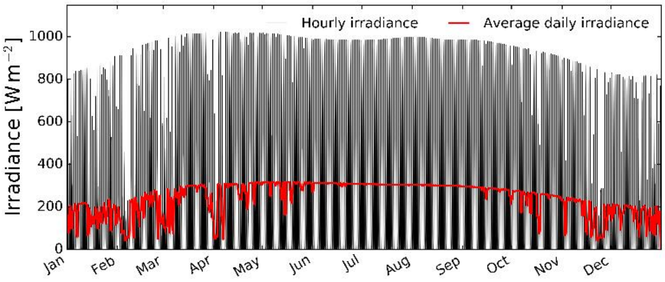

Figure 3: Solar irradiance of Astypalaia for 2005 from www.soda-is.com.

3.2 Remote community in the North of Scotland

The island Westray in the Orkney Islands in the North of Scotland is used as the second case study. Westray has around 600 inhabitants which we assume are spread over 335 domestic buildings. The electricity demand is scaled from the UK national demand and given in Figure 4. The annual electricity demand is 1480 MWh.

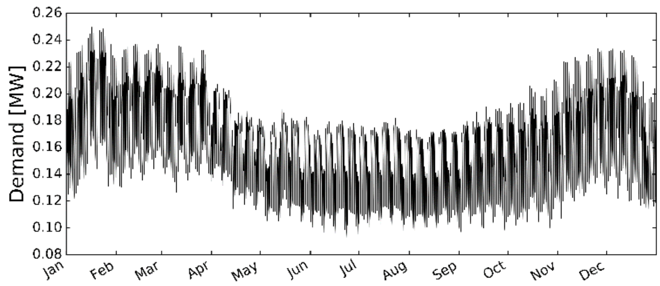

Figure 4: Synthetic electricity demand for Westray in the North of Scotland.

The HES for Westray consists of diesel generators, battery energy storage, wind turbines and solar PV panels. We didn't have wave resource data and thus no wave energy converters were included. The wind and solar resource are given in Figure 5 and Figure 6. The wind resource in Figure 5 shows some overlap with the electricity demand in Figure 4. This is due to the increase in wind speeds during the winter in the North of Scotland. On the other hand, the solar resource in Figure 6 has its peak during the summer and is much smaller than the solar resource in Astypalaia shown in Figure 3.

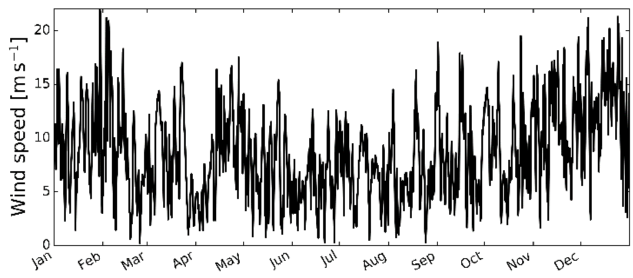

Figure 5: Hourly wind speed at 10 metre above sea level.

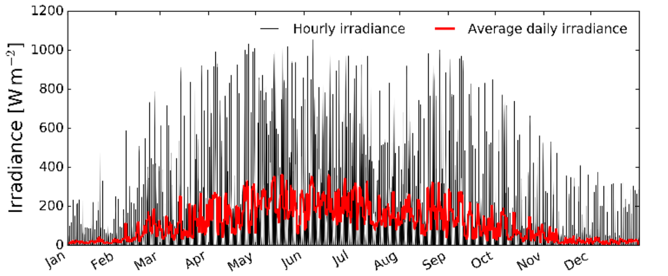

Figure 6: Solar irradiance of Westray for 2005 from www.soda-is.com.

3.3 HES components

The electricity demand of the two case studies is between 0.1 MW and 1.8MW thus for the design of the HES electricity generation units which can supply this demand are picked. The specifics of the diesel generator, wind turbine, wave energy converter and solar PV panels are:

- Perkins 175 kW diesel generator: hourly diesel consumption at rated capacity is 48 litres;
- Vestas V27 wind turbine: hub height 35 m; rated power 225 kW; cut-in, rated and cut-out speed of 3.5, 14 and 25 m/s;
- Wavestar 600kW wave energy converter: see [6] for details;
- Solar PV panel with an efficiency of 16%.

It is assumed that all inverters have an efficiency of 97%. Both the charging and discharging efficiency of the battery was assumed to be 95% which gives a relatively high but not unreasonable round-trip efficiency of ~90%.

4 Results and discussion

The two case studies are optimised without DSM and with various levels of DSM: 5% for 5 hours; 10% for 5 hours; 20% for 5 hours; and 10% for 10 hours. Multi-objective optimisations were performed with respect to LCOE and the emissions of CO_2 per kWh.

4.1 Results for Astypalaia

The Pareto front in Figure 7 shows that HES with and without DSM can reach cost parity with the conventional energy system while also producing less than 10% of the CO_2 emissions of the convention energy system. The introduction of a small amount of DSM moves the Pareto front in the direction of the origin, i.e. reduces both the electricity cost and the emissions.

The results in Table 1 show the emissions and electricity costs for the DSM cases with the HES configuration which without DSM achieves cost parity with the conventional system. It is evident that in this case the emissions drop more significantly compared to the cost. The main costs are the capital costs which stay constant in this case and thus the low drop in electricity costs is only due to the reduced fuel use. On the other hand, the emissions are reduced by up to 16%.

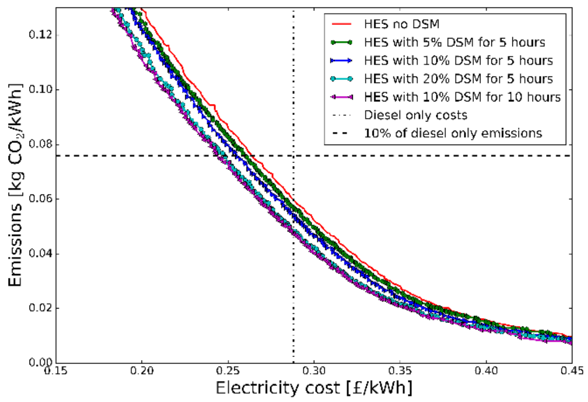

Figure 7: Pareto front for the HES for Astypalaia with and without DSM.

For a fixed shift window length, the emissions reductions are almost linear with increasing shiftable load. For Astypalaia the case with 10% DSM for 10 hours is slightly better than the case with 20% DSM for 5 hours.

	Emissions [gCO_2/kWh]	LCOE [£/kWh]
No DSM	59.7	0.288
5%, 5 hours	57.2	0.287
10%, 5 hours	55.2	0.286
20%, 5 hours	50.9	0.285
10%, 10 hours	49.9	0.284

Table 1: Emissions and LCOE of the HES with DSM for the configuration of the HES without DSM which achieves cost parity with the diesel only case.

Table 2 shows results for systems with the same electricity costs or emissions, respectively, but with varying configurations. The left column shows that the HES with DSM can achieve emissions savings up to 21% compared to the system without DSM if cost parity with the diesel only configuration is required. The right column shows that DSM can reduce the LCOE by up to 8% compared to the system without DSM if up to 10% of the diesel only emissions are allowed.

	Emissions at LCOE as the diesel only case [gCO_2/kWh]	LCOE at 10% diesel emissions [£/kWh]
No DSM	59.7	0.264
5%, 5 hours	56.9	0.260
10%, 5 hours	54.4	0.255
20%, 5 hours	48.4	0.248
10%, 10 hours	47.0	0.244

Table 2: Emissions and LCOE of the HES with and without DSM at the LCOE of the diesel only system and with 10% of the diesel only emissions, respectively.

It is interesting to note that the Pareto front in Figure 7 becomes flatter for LCOE larger than 0.35 £/kWh, i.e. there is a long tail with low but non-zero emissions. This is due to the large seasonal variation in demand: to meet the summer demand peak would require a massively oversized renewable generation capacity.

The installed energy/power of the different units in the HES are shown in Figure 8. While the installed battery and solar PV capacity increase monotonically with increasing costs, the installed wind turbine capacity decreases before increasing again at high LCOE. This agrees with the fact that the wind generation is about 10% cheaper per kWh than the solar PV generation and thus the wind turbines produce lower cost electricity if all of it is used. At low LCOE and thus high emissions a significant fraction of the electricity is provided by the diesel generators and not much of the renewable generation is curtailed. For high LCOE on the other hand the emissions are low but also a significant part of the renewables needs to be curtailed. For this case the solar PV panels are advantageous due to the daily cycle and the good solar resource in Astypalaia (Figure 3). The wave energy converter is only chosen for configurations with costs above 0.35 £/kWh. This is due to the higher capital cost and lower capacity factor compared to the wind turbines.

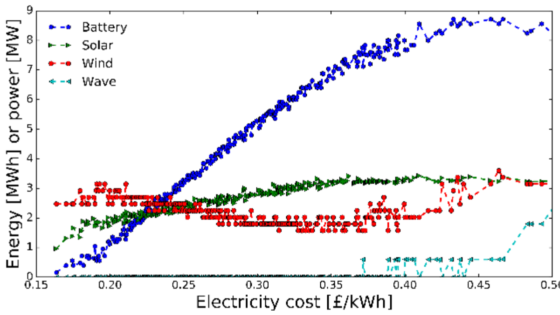

Figure 8: Installed energy/power capacity of the HES in Astypalaia for the case with 5% DSM for 5 hours.

4.2 Results for Westray

The optimisation results for Westray show a similar trend to the Astypalaia results as shown in Figure 9. A noteworthy difference is that the Pareto front is generally flatter over the complete cost range. This is clearly seen in the fact that while the crossing of the 10% of diesel only emissions line is at almost the same position as in Figure 7, the crossing of the cost parity with the diesel only case line is at higher CO_2 emissions. As a consequence the emissions savings through DSM for the cost parity case are only up to 14% while the cost savings for 10% of diesel only emissions is up to 8% (the same as for the Astypalaia case).

It is interesting to note that the 20% DSM for 5 hours case is slightly better than the 10% DSM for 10 hours case in contrast to the Astypalaia case study where it was the other way round. The installed energy/power of the different units in the HES presented in Figure 10 show that wind turbines are the main renewable generator for a HES in Westray. This is not surprising given the good wind resource (Figure 5) and the mismatch between electricity demand and solar resource (Figure 6). For a LCOE of around 0.25 £/kWh the system contains battery storage for about 2 hours of average demand which is slightly less compared to the case for Astypalaia.

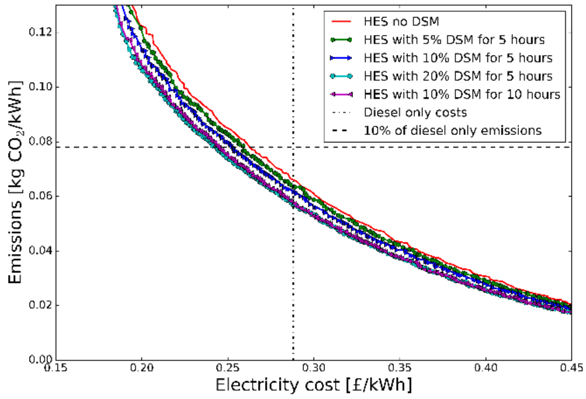

Figure 9: Pareto front for the HES in Westray with and without DSM.

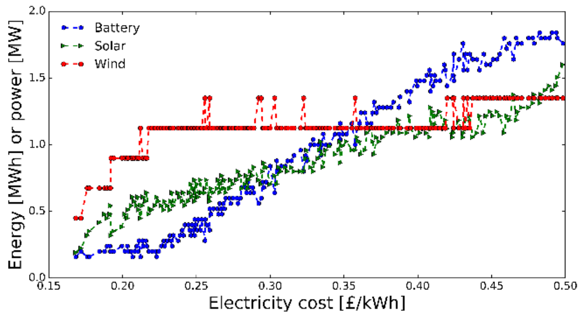

Figure 10: Installed energy/power capacity of the HES in Westray with 5% DSM for 5 hours.

5 Conclusion

In this contribution the effect of adding DSM in the form of flexible demand was investigated. Flexible demand defined as a percentage of the total demand and a shift window was added to the in-house HES simulation and optimisation framework. The framework was used to evaluate the effect of different levels of DSM (shiftable demand and shift window length) on the LCOE and CO_2 emissions of HES for two off-grid islands: Astypalaia in the south of the Aegean Sea and Westray in the Orkney Islands. The multi-objective optimisations with respect to LCOE and emissions showed that low levels of DSM, e.g. 10% shiftable demand for 10 hours, can reduce the emissions by up to 21% for Astypalaia and up to 14% for Westray. The LCOE for both cases can be reduced by up to 8%.

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